MnROAD Environmental Factors that Affect Ride

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Abstract

The Minnesota Department of Transportation (Mn/DOT) built the Minnesota Road Research Project MnROAD between 1990-1993. The 2.5-mile low volume road and the 3.5-mile mainline consists of a 2-lane roadway that originally contained gravel, hot mix asphalt, and concrete test cells designed for both low volume roads and interstate traffic. The mainline interstate cells are trafficked by public interstate traffic and the low volume road has a Mn/DOT 5-axle tractor-semi-trailer to simulated conditions of rural roads in two load configurations, resulting in the same equivalent axle loads or ESALS. MnROAD is located in a wet freeze zone that has affected both its base and subgrade materials with seasonal frost movements. This movement has slowly deteriorated each test cells ride over time. MnROAD has monitored the frost movements using frost pins and has measured the ride (international ride index – IRI) using high-speed profilers over for the life of the project. This paper investigates the loss of ride from both environmental and traffic loadings and how they have combined to cause the deterioration of ride over the last 10 years at MnROAD. The findings suggest that our current process to develop a mechanistic empirical design is currently missing the fact that seasonal differential frost movements play an important role in pavement performance in northern climates and need to be taken into account.

Background

The Minnesota Department of Transportation (Mn/DOT) constructed the Minnesota Road Research Project (MnROAD) between 1990 and 1994. MnROAD is located along Interstate 94 forty miles northwest of Minneapolis/St.Paul and is an extensive pavement research facility consisting of two separate roadway segments containing
51 distinct test cells. Each MnROAD test cell is approximately 500 feet long. Subgrade, aggregate base, and surface materials, as well as, roadbed structure and drainage methods vary from cell to cell. All data presented herein, as well as historical sampling, testing, and construction information, can be found in the MnROAD database and in various publications. Additional information on MnROAD can also be found on its web site at: http://mnroad.dot.state.mn.us/research/mnresearch.asp.

Picture 1 – MnROAD Mainline and Low Volume Road

Low Volume Road

Parallel and adjacent to Interstate 94 and the Mainline is the Low Volume Road (LVR). The LVR is a 2-lane, 2½-mile closed loop that contains 20 test cells. Traffic on the LVR is restricted to an MnROAD operated vehicle, which is an 18-wheel, 5-axle, tractor/trailer with two different loading configurations. The "heavy" load configuration results in a gross vehicle weight of 102 kips (102K configuration). The “legal” load configuration has a gross vehicle weight of 80 kips (80K configuration). On Wednesdays, the tractor/trailer operates in the 102K configuration and travels in the outside lane of the LVR loop. The tractor/trailer travels on the inside lane of the LVR loop in the 80K configuration on all other weekdays. This results in a similar number of ESALs being delivered to both lanes. ESALs on the LVR are determined by the number of laps (80 per day on average) for each day and are entered into the MnROAD database. Appendix A contains cell layouts and designs.

MnROAD Mainline

The mainline consists of a 3.5-mile 2-lane interstate roadway carrying “live” traffic. The Mainline consists of both 5-year and 10-year pavement designs. The 5-year cells were completed in 1992 and the 10-year cells were completed in 1993. Originally, a total of 23 cells were constructed consisting of 14 HMA cells and 9 Portland Cement Concrete (PCC) test cells. Traffic on the mainline comes from the traveling public on westbound I-94. Typically the mainline traffic is switched to the old I-94 westbound lanes once a month for three days to allow MnROAD researchers to safely collect data. The mainline ESALs are determined from an IRD hydraulic load scale was installed in 1989 and a Kistler quartz sensor installed in 2000. Currently the mainline has received roughly 5 million flexible Equivalent Single Axle Loads (ESALS) and 7.8 million Rigid ESALS as of December 2004.
**MnROAD Instrumentation and Performance Database**

Data collection at MnROAD is accomplished with a variety of methods to help describe the layers, the pavement response to loads and the environment, and actual pavement performance. Layer data is collected from a number of different types of sensors located throughout the pavement surface and sub-layers, which initially numbered 4,572. Since then we have added to this total with additional installations and sensors types. Data flows from these sensors to several roadside cabinets, which are connected by a fiber optic network that is feed into the MnROAD database for storage and analysis. Data can be requested from the MnROAD database for each sensor along with the performance data that is collected throughout the year. This includes ride, distress, rutting, faulting, friction, forensic trenches, material laboratory testing and the sensors measure variables such as temperature, moisture, strain, deflection, and frost depth.

**Examination of Frost PIN Elevation**

Part of the MnROAD experiment included the study of frost effects. The frost study component of MnROAD included the installation of a number of temperature and moisture sensors in the pavement cells and the installation of ‘Frost Pins’ at approximate 50-foot intervals in the middle of each lane. The elevation of these ‘Frost Pins’ were measured at least 80 times over the first four years and stored in the MnROAD database. The elevations were made with an electronic bar code rod and level that is capable of providing elevation readings to the 0.1 mm (0.004 in.) resolution. The ‘accuracy’ of the elevation readings were much lower than the instrument resolution because of operator and environmental factors, but the accuracy should be approximately on the order of 1 to 2 mm (0.04 to 0.08 in.).

The elevation data not only provides information on frost heave activity, but also provides information that is useful for the analysis of design presumptions and information that might relate to mechanisms that control the component of longitudinal profile that relates to ride. One design aspect that can be evaluated is the role of materials (particularly thick subbase layers) that are not as frost heave susceptible in the structural performance of a pavement. The ride aspect that can be examined is to identify if the subgrade type, or thick subbase layers have any effect on seasonal changes in longitudinal profile that affect ride.

To examine these issues, two pairs of test cells (asphalt Cells 25-26 and concrete Cells 36,39) were selected as shown in Figure 1 along with Cell 27 (thin asphalt) for another comparison. The two pairs are quite similar except one has a thick sand layer (R-value=70) under the pavement structure and the other has a clay layer (R-Value=12). It is commonly accepted that sand is not susceptible to the development
of frost heave. This paper examines some MnROAD data, which provides better insight into the selection and design of underlying unbound layers and how they can significantly affect pavement performance. The data shows that there is a potential that the properties of the underlying layers that undergo large volume change relates to structural and functional performance, and that with development, can be included more into pavement design.

![Figure 1 – MnROAD Test Cells used for Comparison](image)

**Functional Design Issues**

What factors are there that can affect changes in longitudinal profile over the typical life of a pavement? Changes in profile are generally attributed to the cumulative effects of traffic over the years. The mechanics of the actual change in profile is not fully understood however. Pavement design procedures are oriented toward the control of such things as cracking, faulting, and rutting. A good ride is expected to be retained, if these structural modes of deterioration are controlled. Therefore, with the new mechanistic-empirical pavement design methods being developed, designers currently do not have any means of selecting materials based on their relationship to profile performance, or the means of predicting longitudinal profile characteristics or functional performance based on material properties.

What brings the mechanisms that relate to longitudinal profile changes into question is the ride performance of the Mn/DOT asphalt highways as defined in the Mn/DOT Pavement Management System (PMS). After the pavements are about 18 years old, they tend to approach a similar ride value, regardless of how smooth they were initially. Also, the PMS data indicates that there is very little load related cracking occurring (almost none) and the majority of the distress is environmental in nature (transverse cracking). The current Mn/DOT pavement design procedure typically results in pavements that do not develop fatigue cracking. Therefore, a mechanistic/empirical design system that controls strains to control the development of fatigue cracking does necessarily result in a design that insures that the pavement stays smooth. Why is that? To examine this question about factors that might affect the longitudinal profile, frost pin data from MnROAD was evaluated. Although the frost pin data is nowhere near sufficient to evaluate profile as it relates to ride, it can
be used to examine if changes in surface elevation of pins relevant to the other pins in a test cell might relate to changes in longitudinal profile.

The frost pins on the MnROAD cells are placed at 50-foot intervals between the wheel paths for flexible cells and at mid-panel locations on rigid cells with nominal spacing of 50 feet or less down each 500-foot test cell. Elevation measurements at 50-foot intervals cannot be used to infer ride characteristics, but these differential elevation changes might relate well to ride performance. The premise here is that the elevation changes that occur are due to factors that are not related to traffic, such as seasonal moisture and temperature changes, and frost heave.

Mn/DOT has used deep (3 to 5-foot) subcuts as a method to improve subgrade uniformity. These subcuts are often mixed and backfilled with the same native soils that were excavated. The native soils are placed in controlled lifts and at controlled moisture content and compacted to a specified density with the expectation that any vertical movement from frost heave will be uniform. Figure 2 and 3 shows the pin elevations taken over a four-year period on MnROAD Cells 26 and 39 respectively. Cell 26 is a 5.9 inch Full-Depth asphalt pavement and Cell 39 is a 6.4-inch concrete pavement on a 5-inch aggregate base. Both cells are on the low volume loop and are constructed over a clay subgrade. The cells are on slight grades with respect to the pin numbers so the pin elevation plots are evenly spaced at different elevations. The elevation changes all follow a similar pattern with a slight heave of about 1.1 inches of vertical movement per pin, on average, for both cells. The pin elevation changes, however, vary from pin to pin. Pin 2604 in Cell 26, for example, had a 2.7-inch range of vertical movement and Pin 2612 had only a 0.826-inch range in vertical movement. The elevations were taken with an electronic bar-code reading rod and level, which is capable of resolving elevations to 0.1 mm or about 0.004 inch or 0.0003 foot. The actual precision of the elevations are perhaps a magnitude or so less than that, but with sufficient precision to tell if there is a relative difference in elevation changes between pins, which is the interest here.
For comparison, Figure 4 and 5 are of Cells 25 and 36 respectively. These cells are of similar pavement structures as Cell 26 and 39, but were constructed on a select granular subgrade. The changes in pin elevations are much less than that experienced by Cells 26 and 39. The average vertical movement range on Cell 25, the asphalt cell, is about .33 inch and the average movement range on Cell 36, the concrete cell, is...
about .5 inch. The range of vertical movement measured on the pins of the two cells constructed on a select granular subgrade is much less than for similar cells constructed on clay subgrade, as would be expected because the select granular material is much less susceptible to the development of frost heave. There still is, however, some vertical movement, and if random enough, this vertical movement can possible lead to pavement roughness, but at a much slower pace than possible for pavements constructed on clay subgrade.

Figure 4 – Cell 25 Frost Pin Elevations (asphalt on a sand subgrade)

Figure 5 – Cell 36 Frost Pin Elevations (concrete on select granular subgrade)
The degree to which a pavement is considered smooth or rough relates to how much the actual profile deviates from an idealized profile. The current technology for measuring profiles for roughness determination process is the measure of the deviation from an line as defined by a profilograph, or a line defined by an inertial plane. Another way (although a non-traditional way) of expressing roughness is to express the change in elevation from a ‘true’ profile. A true profile could be expressed as a survey grade, either on grade tangent, or on vertical curves that are described by a second order expression in traditional grade calculations. Some statistical characterization of these deviations would characterize some aspect of roughness. Deviations from ‘true profile’ at close intervals such as two to ten-foot intervals probably relate better to vehicle passenger’s perspective of ride. Since the frost pins are at about 50-foot intervals, the deviation from ‘true profile’ is less related to ride, but still can be looked at to see how these deviations change as a function of subgrade material and as a function of time.

As indicated earlier, one of the objectives of the Mn/DOT grading practice of deep excavation (3 to 5 feet below the top of the grading grade) is to establish material uniformity, which is thought to relate to longer service life for the pavement. In 1995, Mn/DOT revised the pavement design standards to include the replacement of up to 30 inches of the subgrade with select granular material. Other agencies, counties and cities and the surrounding states, typically do not subcut nearly as much as Mn/DOT does, nor do they use select granular material to the same extent. While there is feeling among the Mn/DOT pavement engineers that the subcut effort is worthwhile, there have been no specific studies to compare pavement performance as a function of subcut depth.

It should be noted that all of the MnROAD cells were sub cut to at least five feet below grading grade, so the information that MnROAD can provide relates more to the variation in subgrade material, moisture content, and other parameters than to the depth of subcut.

In an attempt to evaluate the relative movement of these frost pins in a manner that might relate to roughness, the first set of elevations measurements was used to establish a ‘true profile’ by fitting a mathematical profile line though the frost pins. If the cell appeared to be in a vertical curve, or partially in a vertical curve, the Excel ‘Solver’ function was used to estimate grade coefficients that minimized the square of the deviation of each pin to the ‘true profile’ line. Once this line was established, all frost pin elevations were compared to this ‘true profile’ line. For each elevation measurement set, a standard deviation of the elevation differences was calculated and expressed in inches.

Figure 6 and 7 are plots of how the frost pin elevation’s deviation from ‘true profile’ changes with time. Figure 6 shows that the asphalt cell-26 on clay subgrade is developing more deviation from the ‘true profile’ at a much faster rate than the asphalt cell-25 constructed on select granular sand subgrades. This behavior meets
with our expectations, that clay subgrades are more active than granular sand subgrades with respect to vertical movement.

Figure 6 – Cell 25 and 26 comparison of subgrade effect on asphalt pavement profile

Figure 7 shows that Cell 39, the concrete cell on clay, is also experiencing an increase in the standard deviation of the frost pin elevations from ‘true profile’ but at a slower rate than shown by the Cell 26, the asphalt cell on clay. Cell 36 is actually showing a decline in the standard deviation of the frost pin elevations from ‘true profile.’
Examination of the frost pin elevations for these four cells show the concrete cells have less vertical movement/activity than the asphalt cells. It should be noted that both Cell 25 and 26 are Full-Depth Asphalt and that an asphalt pavement over an aggregate base section in Cell 27 might be less active, but there are no comparable aggregate base cells built on clay and on select granular. Cell 27 is an asphalt pavement 3.3 inches thick constructed on 11 inches of Class 6 “crushed granite” aggregate base on clay could be compared to Cell 26 to see what the effects of the aggregate base might be, but the asphalt is also much thinner at 3.3 inches compared to 5.9 inches for Cell 26.

The overall frost pin elevation plots for Cell 27 are shown in Figure 8 and the standard deviation of the elevation changes are shown in Figure 9. The increase in the standard deviation of pin elevation from a ‘true profile’ for Cell 27, however, is much higher than for Cell 26. Further examination of the elevations show that this increase in standard deviation of elevation deviation from ‘true profile’ is due to settlement of three frost pins, 2706, 2708, and 2710 as shown in Figure 10. Figure 10 shows the elevation change of each of the frost pins from the ‘true profile’ and it shows that pins, 2706, 2708, and 2710 settled about 1.5 inches over the time of monitoring. Since the magnitude of movement of these pins are high, the corresponding standard deviations of the pin movements due to settlement of localized areas of fatigue cracking in the cell. Removing those three pins from the standard deviation calculation shows that the remaining pins are showing no corresponding increase in movement as indicated in Figure 11.
Figure 8 – Cell 27 Frost Pin Elevations (asphalt on granular base over clay subgrade)

\[ y = 0.1481x + 0.2866 \]

\[ R^2 = 0.9439 \]

Figure 9 – Cell 27 Standard Deviation of frost pin elevation changes

\[ y = 0.1481x + 0.2866 \]

\[ R^2 = 0.9439 \]
The question posed earlier relates to how the frost pin elevation changes relate to the longitudinal profile used to calculate the International Roughness Index (IRI) or ride. Figure 12 and 13 shows the ride (IRI) on Cells 25 and 26 and Cells 36 and 39 respectively. The frost pin activity for the two asphalt cells examined, Cells 25 and 26, are certainly consistent with the change in IRI. Cell 25 with the granular sand
subgrade has less frost pin activity than Cell 26, which is on a clay subgrade, and the IRI growth for Cell 25 is less than for Cell 26.

The two concrete cells examined (Cells 36 and 39) do not show any real difference in IRI development over the time when the frost pins were monitored. The frost pin activity of section on clay subgrade (Cell 39) is more than the section on granular subgrade (Cell 36), as would be expected, but that movement does not show up in a change in ride (IRI). An examination of the inertial profile data collected by the profilers may show some difference, but at a wavelength that IRI is not sensitive to. The rigid nature of the dowelled concrete panels along with the conservative designs for the original MnROAD concrete cells controls the wavelength of this random change in elevation. A related question, however, for the concrete pavement cells is the consistency of the underlying support for the concrete as these elevation changes develop. After a period of time, the concrete on clay might have less consistent support than the concrete on granular. Non-uniform support could be more of a structural issue than the lower k-value provided by the clay.
The IRI of Cell 27, a thin asphalt section with a granular base on clay subgrade, increased at a much higher rate than for Cell 26. As discussed earlier, the frost pins showed that a section of Cell 27 was settling and the increase in IRI seemed to relate better to the overall frost pin movement as shown in Figure 14 than just the frost pins that did not settle as shown in Figure 10. The relationship between frost pin activity and IRI seems to stay in the same relative order when Cell 27 is added into the comparison, however, the activity on Cell 27 not only includes the seasonal frost heave but also includes a settlement, which is generally not considered to be the typical type of environmentally driven movement. Cell 27 had other issues the certainly could relate to the rate of IRI increase such as the asphalt thickness in areas being closer to two inches than the planned three inches thus causing the fatigue cracking in many parts of this test section.
Conclusion

This paper examined seasonal frost movements over a four-year period on MnROAD’s low volume road along with ride data collected since 1994. The findings suggest that our current empirical design process and the future mechanistic empirical design process is currently missing the fact that seasonal differential frost movements in unbound pavement layers play an important role in pavement performance in northern climates.

Some observations from this paper include:

- Many states including Minnesota use deep 3-5 foot subcut into the existing subgrade to reduce the effects of differential frost heave (MnROAD was subcut 5 feet) but the frost pin data shows the frost heave is not uniform within each test cell and affects the ride and pavement performance.

- MnROAD cells with a clay subgrade experience greater frost heave than select granular subgrade cells (as expected). Below is the average frost heave and standard deviation (SD) change for each cell over 4 years:

  - Cell 26 HMA/Clay = 1.1 inch – Increasing SD
  - Cell 39 PCC/Base/Clay = 1.1 inch – Increasing SD
  - Cell 25 HMA/Sand = .33 inch – Consistent SD
- Cell 36 PCC/Base/Sand = .5 inch – Decreasing SD

- For the asphalt on clay sections, the IRI increased over time as the subgrade heaved with the frost. The asphalt on sand section showed lesser increases in IRI while the subgrade heaved very little. Neither concrete section showed any increase in ride over time, although the concrete on clay section showed significant frost heave. While the ride quality of the pavement is loosely related to differential frost heave of the subgrade, the measurements are taken at different intervals. Many other factors can affect the IRI that are not captured simply by subgrade volume changes.